

The Road to 250 lm/W

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Philips Lumileds

January 29, 2014

Efficiency improvement will continue to drive energy savings

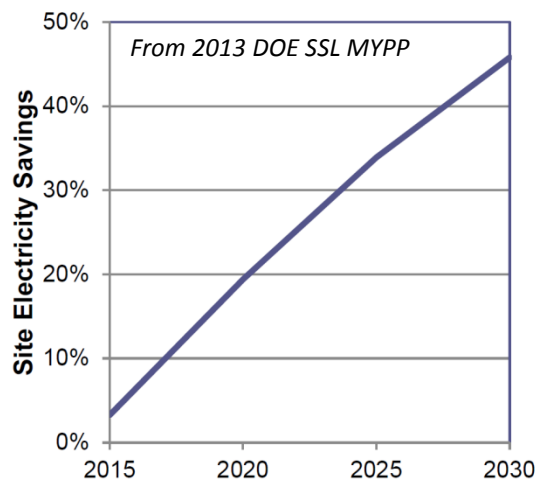


FIGURE 1.1 POTENTIAL SITE ELECTRICITY SAVINGS USING SOLID-STATE LIGHTING

Enablers:

- **Cost reduction**
DOE target: \$0.7/klm @ LED package level
- **Efficiency improvement**
DOE target: 200 lm/W @ luminaire level
250 lm/W @ LED package level



Can we get to 250 lm/W,
and if so, how?

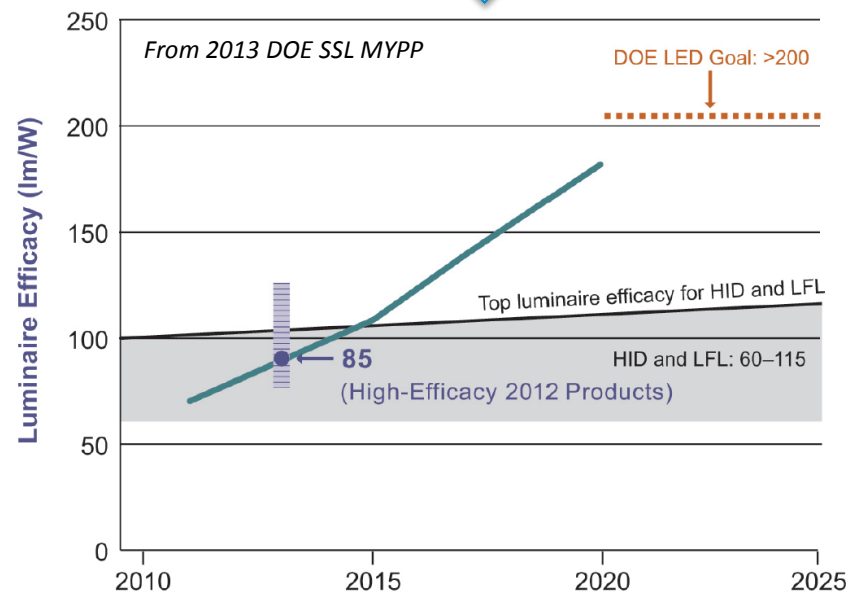
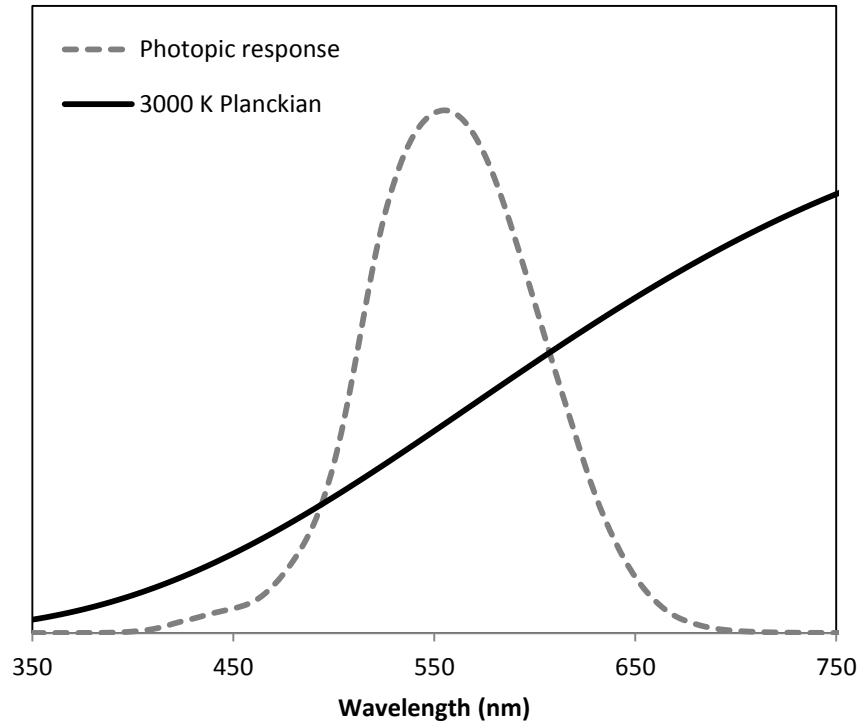


FIGURE 3.7 COMPARISON OF SSL AND INCUMBENT LIGHT SOURCE EFFICACIES
Source: LED Lighting Facts product database

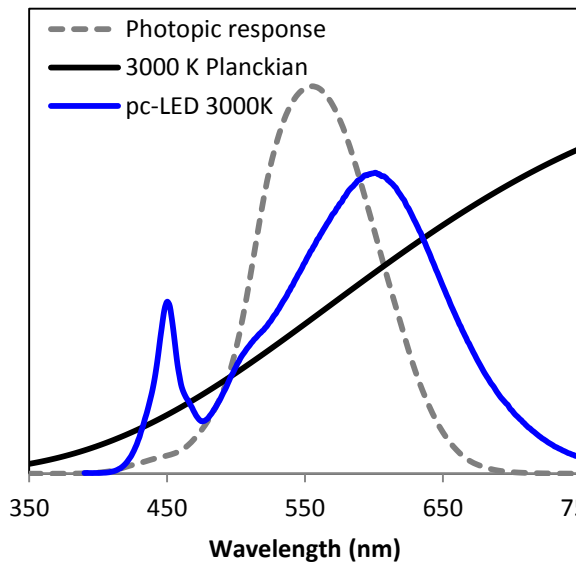
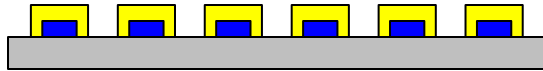
Basic white LED architectures for maximum luminous efficacy



Basic white LED architectures for maximum luminous efficacy

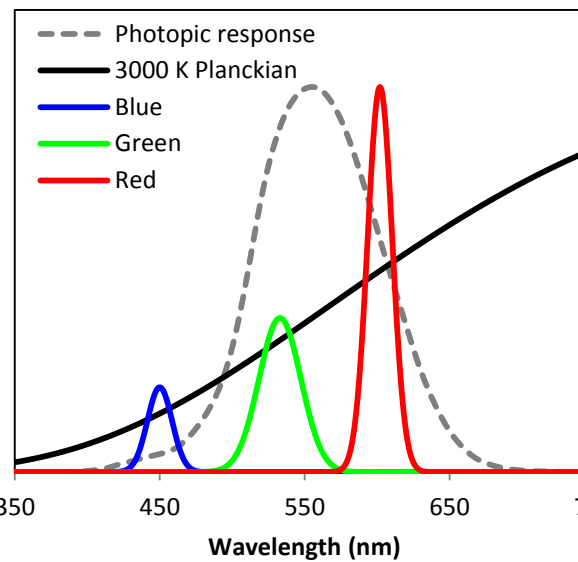
Phosphor-converted LEDs

Blue pump LED + phosphor



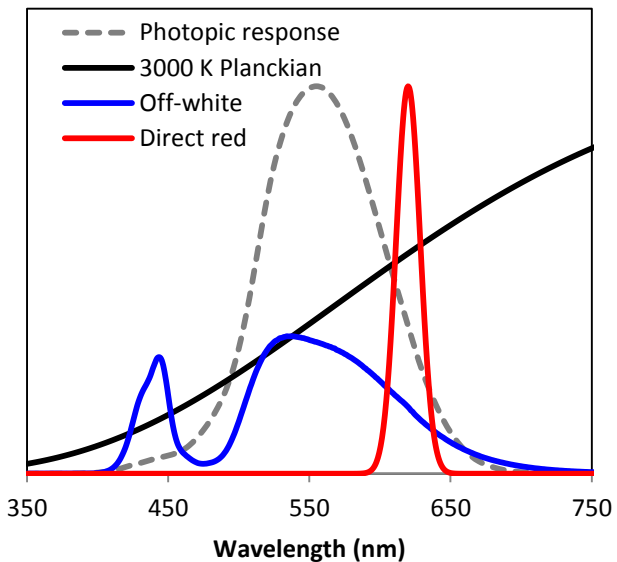
Direct-emitting LEDs

3 or 4 colors



Hybrid LEDs

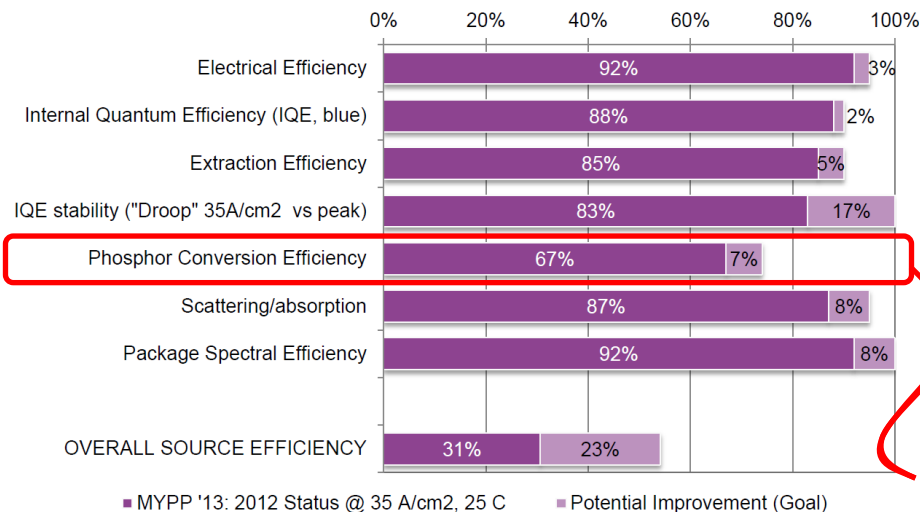
Combining phosphor-converted and direct-emitting LEDs



Source efficiency breakdown

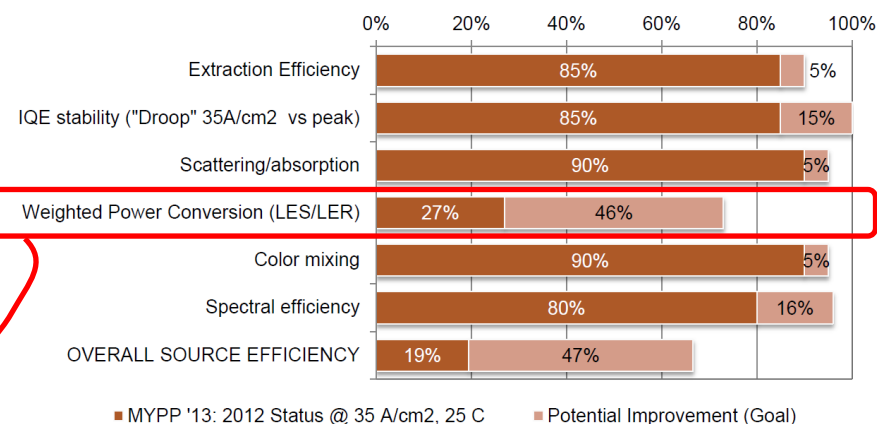
Phosphor-converted LEDs

From 2013 DOE SSL MYPP



Direct-emitting LEDs

From 2013 DOE SSL MYPP



Main loss mechanism

Color-mixed direct-emitting LEDs can **theoretically** reach higher efficacy, but...

SSL adoption will be driven by **practical architectures** that can achieve high efficacy over the **next five years**.

**What are these architectures,
and what R&D challenges need to be overcome to realize them?**

Some boundary conditions for a “practical” architecture

Operating conditions

- Practical operating temperature ($T_j = 85\text{ °C}$ and higher)
(Here we evaluate at $T_j = 25\text{ °C}$ to be consistent with MYPP)
- Practical current density (35 A/cm^2 and higher)

Color quality

- At minimum: CRI $R_a > 80$, unconstrained R_9
- For color-critical applications: CRI $R_a > 90$, $R_9 > 50$
- Meet these requirements at warm white color, CCT = 3000 K

Cost

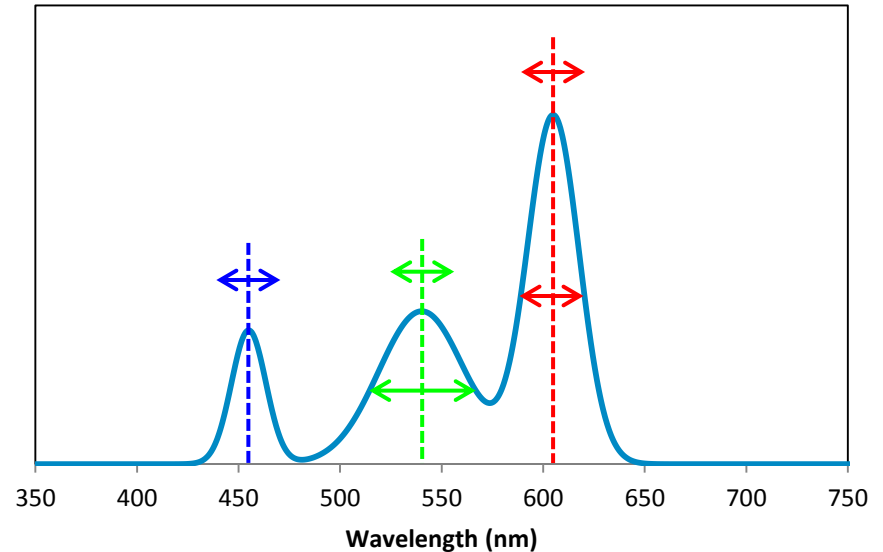
- Include cost of system complexity (color control, mixing optics)

Efficiency of pc-LEDs

Spectral efficiency

2 phosphors, 5 degrees of freedom

- Blue pump wavelength
- Green phosphor center wavelength
- Green phosphor FWHM
- Red phosphor center wavelength
- Red phosphor FWHM



Optimize product **LER * QD**

- Maximum conversion efficiency assuming no scattering and absorption losses in phosphor and package

$$\eta_L = \text{WPE} * \text{CE}$$

WPE: Wall-Plug Efficiency

Power conversion efficiency of blue LED

CE: Phosphor Conversion Efficiency

$$\text{CE} = \text{LER} * \text{QD} * \text{QE} * \text{PE}$$

- LER: Lumen Equivalent of Radiation
- QD: Quantum Deficit
- QE: Down-conversion Quantum Efficiency
- PE: Package Efficiency

Can we meet 250 lm/W with pc-LEDs?

CRI Ra>80, unconstrained R9

- LER*QD up to ~330 lm/W_{opt}
- WPE*QE*PE must be >0.75
- This is ambitious but possible

CRI Ra>90, R9>50

- LER*QD up to ~300 lm/W_{opt}
- 250 lm/W cannot be met
- 225 lm/W is a more realistic target

$$\eta_L = \text{WPE} * \text{CE}$$

WPE: Wall-Plug Efficiency

Power conversion efficiency of blue LED

CE: Phosphor Conversion Efficiency

$$\text{CE} = \text{LER} * \text{QD} * \text{QE} * \text{PE}$$

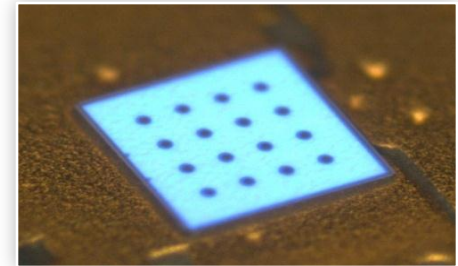
- LER: Lumen Equivalent of Radiation
- QD: Quantum Deficit
- QE: Down-conversion Quantum Efficiency
- PE: Package Efficiency

What do we need to get there?

Pump and conversion efficiency targets

Blue pump LED development

- Peak wavelength 450 nm or longer
- State of the art: WPE \sim 60-65% at 35 A/cm²
- Development path to WPE $>$ 75% at 35 A/cm²
 - Focus on reducing efficiency droop

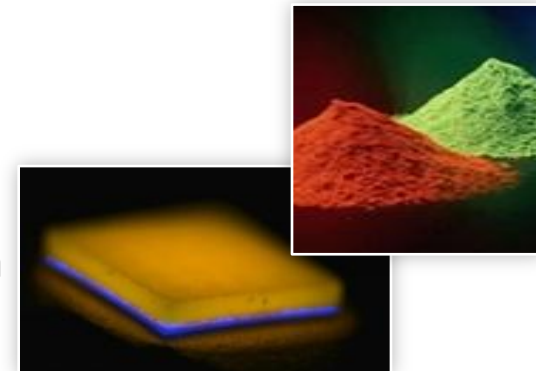


Narrow green phosphor development

- Established green phosphors have QE $>$ 99% but FWHM \sim 100-150 nm
- FWHM $<$ 70 nm is required for maximum LER at CRI Ra $>$ 90
- Challenges: QE and robust packaging

Narrow red phosphor development

- Established red phosphors have QE $>$ 90% at FWHM \sim 100 nm
- Narrow red minimizes spillover in infrared
- Challenges: QE and robust packaging



Efficiency of direct-emitting LEDs

Spectral efficiency

LER optimization similar to pc-LED, but

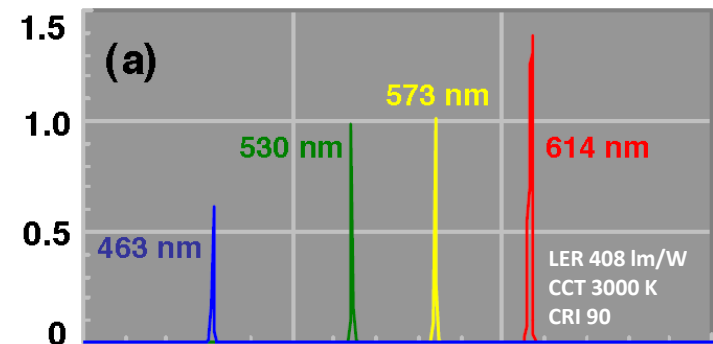
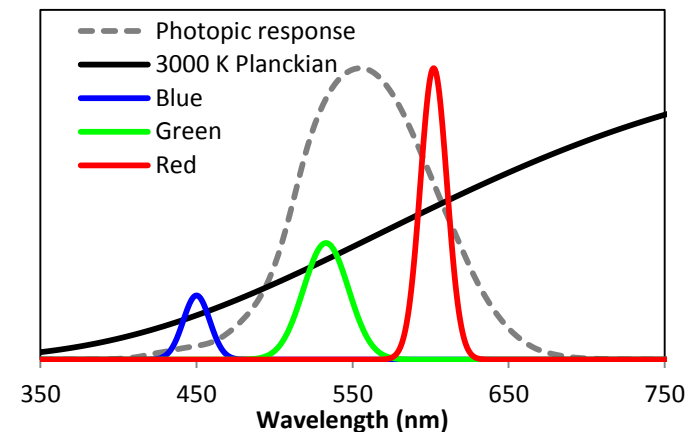
- Green and red peaks are narrow due to direct emission
- No Stokes loss

CRI Ra>80, unconstrained R9

- CRI can be met with 3 direct emitters
- Requires green FWHM ~ 35 nm
- LER ~ 410 lm/W_{opt}

CRI Ra>90, R9>50

- Need more emission in yellow to meet CRI
- Requires either:
 - Additional yellow / amber direct emitter
 - Broader green direct emitter



Phillips et al. Laser and Photon Rev 2007

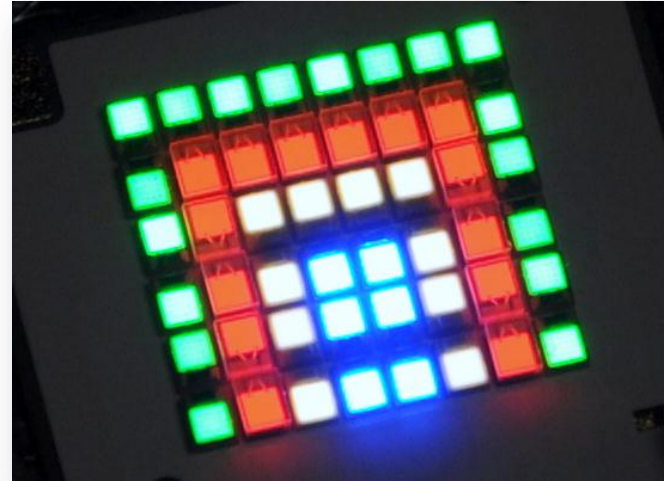
Can we meet 250 lm/W with direct-emitting LEDs?

CRI 80, unconstrained R9

- LER up to 410 lm/W_{opt}
- Need an average WPE of 61%

Not likely to be achieved by 2020

- Blue will be >75%
- Red will be >55%
- Green will be ...25%? 30%? 35%?



With practical WPE assumptions, efficiency will be ~183 lm/W

By 2020, a narrow green pc-LED will have a radiometric efficiency of >55%!

How about hybrid LEDs?

CRI Ra>80, unconstrained R9

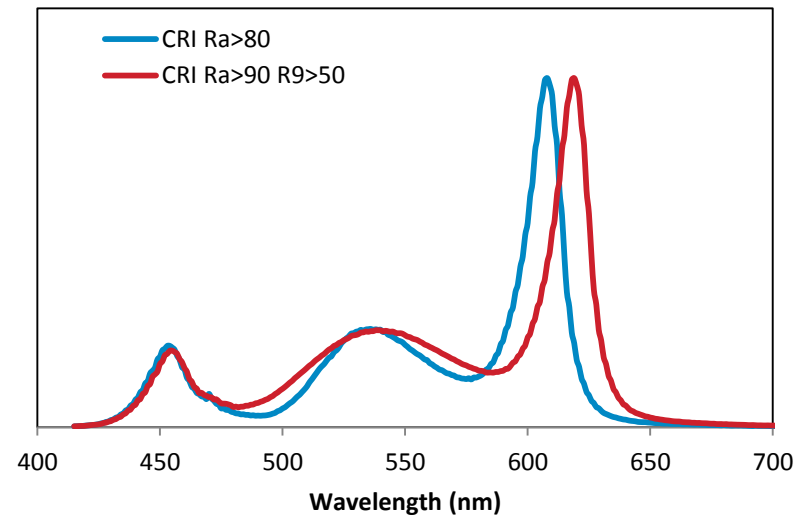
Efficacy up to ~250 lm/W

CRI Ra>90, R9>50

Efficacy up to ~225 lm/W



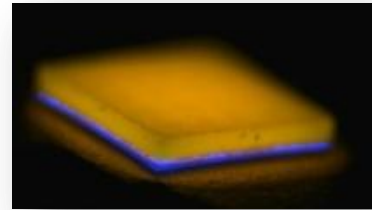
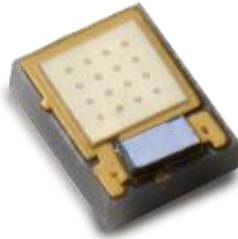
Luminous efficacy		blue WPE					
		50	55	60	65	70	80
red WPE	40						
	45						
	50						
	55						
	60						
	65						



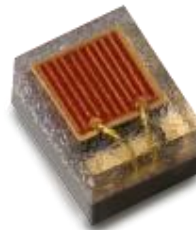
Advantages of hybrid LEDs:

- vs. pc-LEDs: possible alternative for the challenging narrow red phosphor target
- vs. direct-emitting LEDs: efficient emission in the green part of the spectrum

What do we need to get there?



In addition to blue pump and phosphor development...



Red LED development

- Currently at ~ 45%
- Improvements through epi material quality and die architecture
- For practical conditions, hot/cold factor is an additional challenge
 - Currently at ~ 0.6 going from 25 to 85 °C

Efficiency summary (LED level)



Phosphor-converted LEDs
3000 K

- CRI 80: up to 250 lm/W
- CRI 90: up to 225 lm/W



Direct-emitting LEDs
3000 K

- CRI 80: ~183 lm/W
(up to 190 lm/W?)



Hybrid LEDs
3000 K

- CRI 80: up to 250 lm/W
- CRI 90: up to 225 lm/W

System-level view



Phosphor-converted LED systems

Optical performance

- Good source and color-over-angle uniformity enables low-loss optics for directional application

Driver and control complexity

- Single-channel driver
- Color stability is established by LED design
- Fixed color point



Color-mixed LED systems

Optical performance

- Color variation across source area requires color-mixing optics for directional applications
→ efficiency loss ~ 5-10%

Driver and control complexity

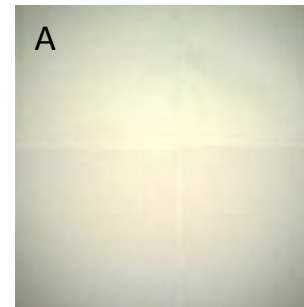
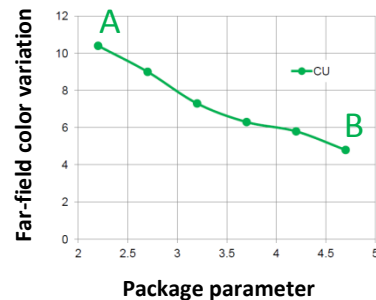
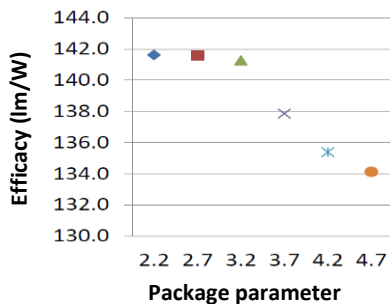
- Multiple channels
- Color stability is established by controls at higher system level
→ adds system cost
- Opportunity to add color tuning functionality

Color mixing for directional applications

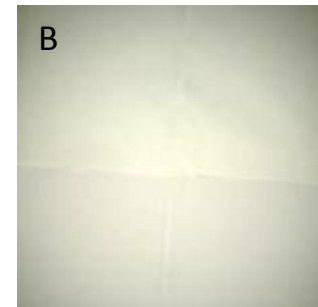
Trade-off between efficiency and color uniformity

Primary color mixing (at package level)

- Die layout on substrate
- Frosted encapsulants and other package-level diffusers



Visible non-uniformity



Improved uniformity

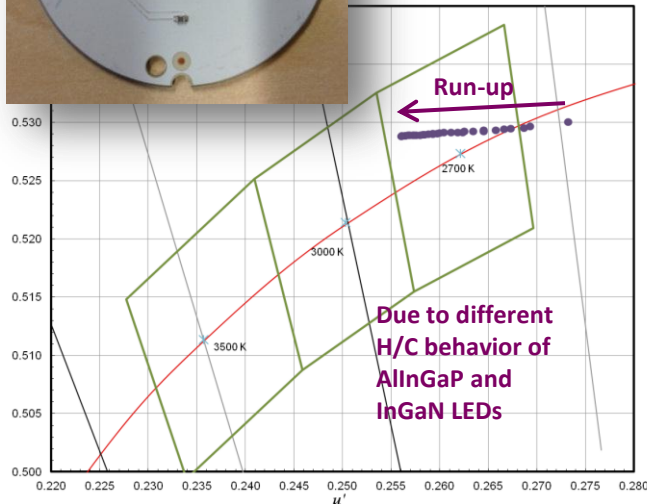
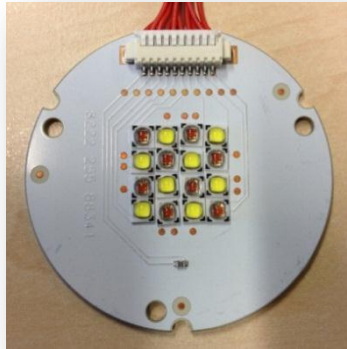
Secondary color mixing

- (Small) mix box
- Mixing reflector / refractor optics

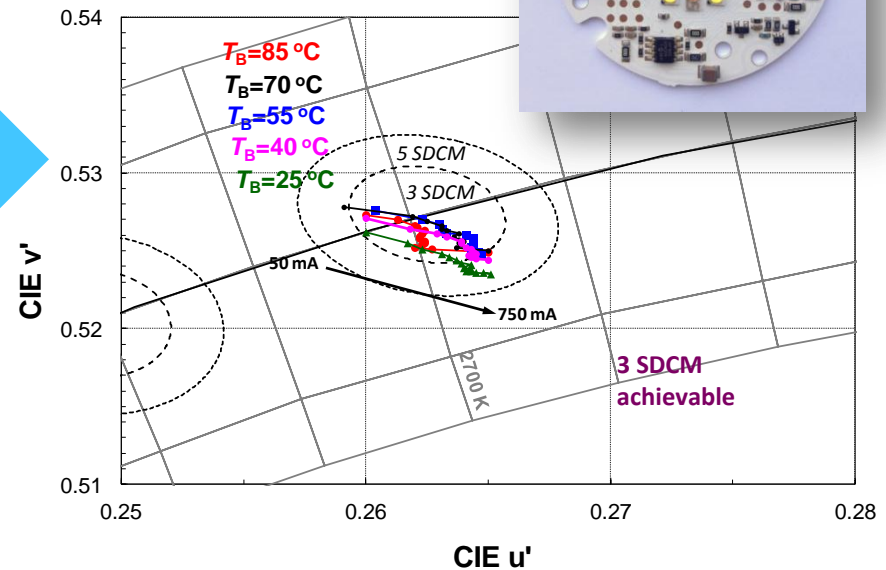
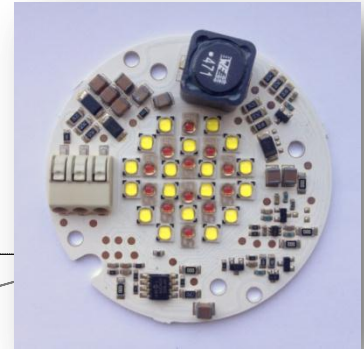


Color stability

Hybrid light engine: Demonstrated 140 lm/W at 3000K, CRI Ra>90, R9>50



Integrate
color control
electronics



Controls will see increasing level of integration:

- Easier calibration, better utilization
- More accurate sensing and control
- Simpler system design / lower cost

See demo and poster #9:
High Power Warm White Hybrid LED
Package for Illumination

Color tuning: *function* as a driver for SSL adoption

....in addition to cost and efficiency

Color tunability

- CCT tuning: comfort, productivity, “dim-to-warm”
- High gamut tuning: design, scene setting, retail, hospitality, entertainment



Current products

- Only a small portion of the total market
- Trade-off between efficiency, color gamut, and cost



By 2020

- Narrow green phosphors enables products with high efficiency and gamut
- Better system integration brings cost of color control down
- Color tuning can become a widespread feature driving further SSL adoption

*Based on the efficacy projections,
hybrid LED products will be the best solution for color tuning applications*

Summary

Efficient LED architectures

- Phosphor-converted LEDs are well positioned to approach DOE targets
 - Up to 250 lm/W for 3000K/80CRI, up to 225 lm/W for 3000K/90CRI
- Hybrid LEDs with direct blue/red and pc-green/yellow
 - are the most efficient color tunable architecture
 - offer an alternative to the challenging narrow red phosphor

Technology challenges

- Blue pump LED: WPE>75% at >450 nm
- Narrow green/yellow and red phosphors
 - QE and robust packaging are challenges
- Package efficiency improvement
 - To get as close as possible to the theoretical maximum CE
- Direct red LED: WPE>55% at 605-618nm
 - Main challenge for practical applications: H/C factor



Thank you